Numerical Analysis of Tribomechanical System Brake Disc-pad for Heavy Duty Vehicles

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Brake system in addition to a steering system actively intervenes to help defuse critical driving situations and prevent accidents from happening come under the heading of active safety. The braking system is expected to be a reliable and durable under normal operating conditions of the vehicle, but also in extreme conditions. For an understanding of the nature of any problem, it is necessary first to realize where the problem originates and to analyze the influential factors. The problems of braking process are characterized by their tribological nature. This paper presents the application of contemporary - alternative materials for making the brake discs for heavy duty vehicles. Analysis was carried in the ANSYS software and the results of the analysis are shown, and also a comparison is made with the conventional discs. The obtained results point to problems that require more effort to develop the MMS materials whose cost and friction characteristics bring advantages over conventional material.

Keywords: Safety, Reliable, Steady, Alternative materials, MMS materials

1. INTRODUCTION

All machines, assemblies and mechanisms consist, as a rule, of several basic movable machine elements [1]. There is relative motion of different surfaces in all these elements that are in direct or indirect contact.

Friction is in most cases, undesirable phenomenon, but not in the brake system. The negative side of friction in any system is heat generated due friction.

The main purpose of brakes is to stop or slow down the vehicle, by friction in the friction pair (brake disc and brake pads), and through contact between the tires and the road. They also need to adapt their effect to traffic conditions, and also to keep the vehicle in a steady state. The kinetic energy is transforming to heat that is generated on disc, and then is dissipated to environment [2]. The braking power in case of emergency braking is far greater than the engine power. The distribution of braking forces on each wheal, or more accurate on the front and rear axle, is very important, and it is essential to prevent traffic accidents.

Modern heavy duty vehicles are more and more equipped with disc brakes, and they use compressed air for transferring force to executive organs – brakes.

Disc brakes have numerous advantages in respect to drum brakes. Of course, they also have some disadvantages, but in most cases, advantages outweigh the disadvantages. One of the biggest advantages is that disc brakes can generate and dissipate a large amount of heat into the atmosphere. Friction occurs only on the surface contact between brake disc and pads. For this reason, the entire disc is not all exposed to friction, but only one part of the disc. The mechanism behind this phenomenon is such that part of the disc that has been exposed to friction and generates the heat in the next moment is no longer subjected to friction, but rotates freely and is exposed only to air, which also serves to release the generated heat due to friction into the atmosphere. In this case, the advantage of these brakes is more efficient cooling that makes them better then other types of brakes. So, they are very suitable for use in heavy duty vehicles, and all this allows that these brakes maintain their characteristics and to be more efficient [3].

The brake discs are made of various kinds of high quality cast irons and rarely from steel. Cast irons are more suitable in respect to steel, because they are very easy for casting and for shaping in the desired form. Furthermore, they are easy for machining and have a high wear resistance. Surface contact that is achieved between cast iron and friction materials provides satisfactory friction coefficients, good properties at elevated temperatures; they are not deforming, and have very good thermal conductivity. In addition to all of this, they have low price.

Aluminum alloys have advanced application, due to the high strength, low density, durability, workability and availabilities. The composites of the aluminum metal matrix are combined with two or more additional ingredients, one of which is the matrix, while the other is the filler (reinforcing). Aluminum metal matrix may be a laminar, fibrous or in a particulate form. In general, the cast iron is used for the production of brake discs; however AMMC (Aluminum Metal Matrix Composite) is selected for several reasons in respect to the cast iron. The main purpose of the discs is to slow down or stop the vehicle or to maintain a constant speed, or to keep the vehicle stationary. Properties of these discs are defined by a suitable hardness, chemical composition, ultimate tensile strength and other necessary characteristics depending on the intended application. When preparing or mixing during the casting of the metal matrix with the composite, one must pay attention to the following factors:

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- it is necessary to achieve a uniform distribution of the reinforcing material;
- it is necessary to achieve a good lubrication between the two main substances, and
- it is necessary to reduce porosity in the casting.

Aluminum alloys are increasingly used in the automotive industry, for reasons of achieving a weight reduction of vehicle and fuel consumption. It can be said that fuel consumption has a direct impact on carbon emissions. Application of composite materials has the potential to improve the braking performance thanks to its attractive properties compared to cast iron.

Joshi et al. [4] is performed a comparison of discs made of cast iron and MMC. Wear in case of cast iron increases with increasing load and sliding speed, while the friction coefficient is constant, but wear of the friction material is slightly higher compared with a cast iron. In the case of the MMC, this is not the case. Load and sliding speed have less influence on the wear. Brake pads have a higher degree of wear when the disc is made of the MMC, so it is necessary to develop new friction materials. The friction forces between the friction material and the MMS is 20% higher than in the case when the same friction material was in contact with the cast iron so that it directly affects the braking performance.

The main objective of Alnaqi et al. [5] was to replace conventional cast iron discs with discs made of aluminum alloys that are lighter. The main challenge is that costs are not high as well as to satisfy the basic requirements of modern vehicles. The influence of different parameters depending on the temperature is analyzed. The disc is made of wrought aluminum alloy coated with alumina in order to strengthen it. An alumina (dehydrated alumina) is coated using the plasma electrolytic oxidation process. The research showed that surface temperature of the disc reached 500ºC, without any damage to the disc brake, except that the friction coefficient is decreased due to fade. In extreme brake conditions, the temperature of brake disc reached 550°C and at this temperature the disc was disintegrated. Authors came to the conclusion that it is not necessary to coat the entire disc because in this way, the heat disipation from the disc to the environment is reduced; it is enough to coat the contact surfaces. It is also analyzed the effects of the coating thickness; which is the best, and they come to the conclusion that the optimum thickness is 30 µm, while the total disc thickness is 12.24 mm. This design of the disc could sustain two different and very extreme braking, if the vehicle's mass was 1400 kg.

During the studies that have been carried out by Adebisi et al. [6], the brake disc was made by the stir casting process. Weight of the disc in comparasion with conventional discs is reduced for 50%. Compared to cast iron discs, the rate of heat dissipation into the environment has increased for 25% for pressure within the range of 1.5 - 2 MPa. In such conditions, there is no excessive heating, which negatively affects the braking process. Furthermore, the results obtained by numerical analysis have a good agreement with the experiment results. In the end, it was concluded that the cast iron disc can be replaced by alternative materials, and in addition they are very profitable.

Kumar et al. [7] have compared AlHMMC (Hybrid Aluminum Metal Matrix Composite) with Al6061. Hybrid alloy has a higher hardness compared to Al6061 for 45%. With a longer sliding distance, the wear resistance of AlHMMC is higher compared to AL6061 for 20-50%, depending on the effects of load and sliding speed. Ingredients that are added to the material during the manufacturing of the brake disc contribute to this. Stable mean friction coefficient is achieved for AlHMMC at a load of 20 N, sliding speed of 6.28 m/s and sliding distance of 2400 m, while for Al6061 can be achieved at 40 N, 4.18 m/s and 2400 m. By optimizing the parameters, it has been shown that at 20 N; 2.06 m/s and 800 m, AlHMMC has a smaller specific wear rate compared to Al6061. It can be said that the wear rate in the first place most affected by the load, then sliding speeds and eventually sliding distance. Based on the observed wear rates for both materials, it has been shown that the sliding speed for Al6061 has an influence of 39.57% and 42.51% for AlHMMC. Applied load for AlHMMC has a greater influence compared to the sliding speed.

The friction coefficient depends on the coating of the brake disc. The braking process is conducted on the dynamometer, and the values were in the range 0.28 - 0.34, that is acceptable for modern braking systems [8]. The coated discs were highly resistant to elevated temperatures, and it was found that at a temperature of about 500ºC disc was not damaged. Disc made of aluminum alloy without the coating, as well as the disc of the MMC could not withstand such severe conditions. Furthermore, the experiment has shown that in the aluminum alloy coated, the surface was uniform and more resistant, unlike the aluminum metal matrix which was also coated. Discs of aluminum alloy coated had a very good performance. However, when reaching a temperature of 550°C it was disintegrated.

Manufacturers of brake discs for various categories of vehicles offer different solutions regarding use the aluminum in brake disc manufacturing. The application of aluminum brake discs, that are one of the most important vehicle assemblies, is primarily intended to reduce the mass of the rotating parts that are responsible for braking distance. Vehicle weight also has influence on fuel consumption, which is one of the prominent demands that are placed in front of each vehicle. Fuel consumption has a direct impact on the emission of carbon oxides from the vehicle, and the fuel consumption is direct related to the vehicle mass.

An example of the latest technologies in the field of braking is the American company Matrix, which not only made the motorcycle brakes, but brakes for NASA and also for the US Army Research Laboratory. Their patent is, in fact, a brake disc made from MMC that is still on pending. They are primarily focused on discs that are installed on the Harley-Davidson and Indian Motorcycles. The company claims that such a disc provides powerful performance and a good adjustment, and they are available for motorcycle manufacturers [9]. The brake disc of Matrix Company is shown in Figure 1. The price of such a disc is 399.00 dollars.

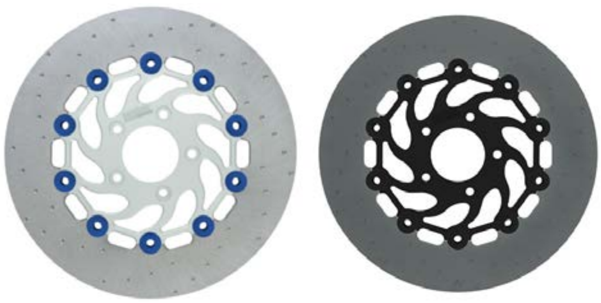

Figure 1: Matrix Company brake discs [10]

Composite brake discs are the latest innovation in braking. They are very light because they are manufactured from aluminum metal matrix which in addition offers a lifetime warranty, but only in cases when used with the appropriate brake pads recommended by the manufacturer. Advantages of such brake discs on motorcycles are the following:

- never corrode;
- generate less dust in the braking process;
- produce ten times less noise in the braking process, and
- five times faster cooling compared to discs of cast iron to a temperature of 750ºC [10].

Tehter is a German company that manufactures brake discs and brake pads for road vehicles. The two-part brake discs of mentioned company consisting of a disc top hat (2) and friction ring (1), made of high carb cast iron, that are connected with rivets, are shown in Figure 2. The use of aluminum for disc brake head can decrease disc's weight for 15-20%, thereby reducing the so-called not suspension mass of a brake disc [11]. Two-piece discs with reduced weight do not affect only on improving the driving properties, but also reduce emissions. They are available in a large number of models of BMW Company. The advantages of two-piece discs are reflected in the following:

- Optimal driving properties by reducing a non suspension mass;
- Fuel consumption reduction;
- Quality improvement of the thermal conductivity, which leads to the reduced thermal stresses, and this reduces oscillations of a brake disc;
- Greater resistance on load that occurs during the braking process, thanks to the optimization of brakes dynamic;
- Better visual appearance of the disc;
- Resistance to corrosion;
- Lower noise level during braking process and
- Less time needed during the production of discs, thanks to the application of screws.

Figure 2: Two-piece brake discs1-friction ring, 2-top hat [11]

Also, two-piece discs are used on trucks. One such brake disc made in Hendrickson Company is shown in Figure 3. These discs are also offered in the catalogs of other manufacturers such as Wabco and Knorr/Bendix [12]. The same as in the case of passenger vehicle brakes, trucks brake disc cover is made of aluminum, while the friction ring is made of cast iron (Figure 3). The reason for this is to reduce the non suspended mass [13, 14].

Figure 3: A two-part disc used on trucks [12]

Application of alternative solutions is now present in trains, too. The brake discs made of aluminum, are reinforced, and as already mentioned reduce the brake system's weight by 50% and also reduce the wear of the brake disc and the brake pads. It can be said that the wear of such a friction pair is much lower compared to the brake disc made of cast iron [15].

Depending on the speed the train can achieve, and also the transit type engaged (maximum permissible speed), a particular type of disc brakes is installed on trains, or more accurate disc brakes that are manufactured from specific materials, Figure 4. If one train can develop a speed greater than 400 km/h, allowed brake discs are discs made of ceramic or cast steel. If the train is moving at speeds up to 200 km/h, it does not need these discs, but can use discs made of aluminum or cast iron. Proper selection of the brake disc and the brake pads has a significant influence on the amount of costs and service life of such components [15].

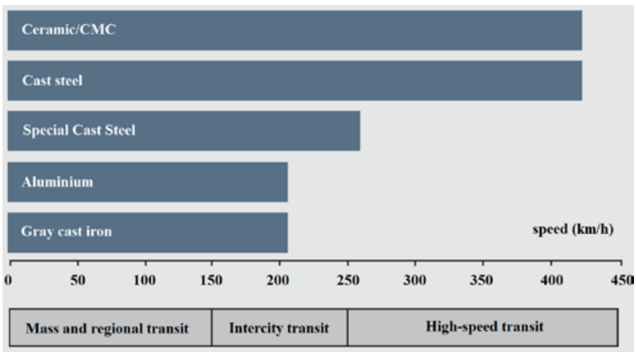

Figure 4: Typical application areas for brake disc's materials for rail vehicles [15]

2. TRIBOLOGICAL STUDY OF BRAKES

It is very difficult to perform an analysis of interaction between the disc and pads because of composition of brake pads, surface structure, and because of differences in mechanical properties of the brake pads' materials [16]. These differences existing among the elements create a barrier to consistency and reproducibility of results. Microscopic research has largest application in terms of the contact geometry, the surface composition and the mechanical characteristics of the contact zone.

Overview of the dynamic contact that is made between the two contact surfaces, in this case, the disc and the brake pads, is very difficult to achieve, primarily because of type of two surfaces that are in contact. A particular problem is the fact that it is possible to see the topography of the area just before or after the braking process. Based on this, it is difficult to determine what happens during the contact, and we can only anticipate.

Surface contact between the brake pads and the disc does not represent two ideal flat surfaces. It can be said, for each of them, to have a plateau, as protrusions and recesses and contact are achieved between these peaks of uneven surfaces. There are two types of contact plateaus: primary and secondary (see Figure 5). The primary contact plateau is the result of the hard fibers of the brake pads that have a lower tendency to wear. These contact plateaus formed a map of channels on the disc, and also influence on the appearance of secondary contact plateaus [16]. Fibers scratch disc leaving channels behind, and the material removed from the disc in this way is collected on the brake pad. Through contact plateaus, the frictional force is achieved. All this has a great influence on the friction that is achieved between the contact surfaces.

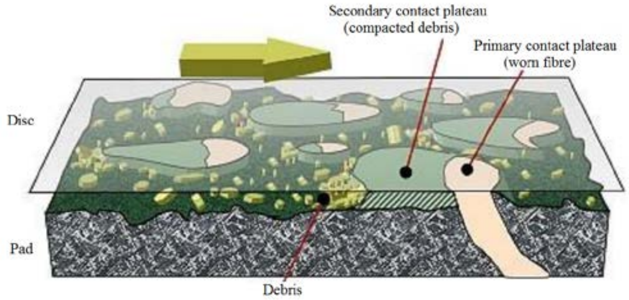

Figure 5: Systematic representation of contact plateaus [16]

It is believed that the wear debris accumulation depends on the wear intensity, the distance between the disc and the brake pads, friction and the normal loads. The formation and growth of secondary contact plateaus can be started in one moment, but only in the case when there are favorable conditions for the formation [16]. Within a thin layer that is formed on the upper layer of the secondary plateaus, the tribofilm has of high density and strength. It can be said that tribofilm has hardness close to fibers used to produce brake pads, while the rest of the film, under the secondary plateaus, is much softer, and this is shown in Figure 6.

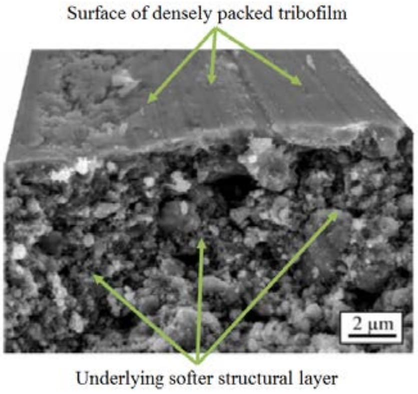

Figure 6: SEM cross-section of secondary plateaus [16]

The lower surface between plateaus is more prone to the accumulation of wear debris, or more accurate these are parts of the brake pad consisted of binders, fillers and friction modifiers. This represents a paradox because the topography remains in a stable condition. Lower areas are never in direct contact, but the stable state of topography indicates that there is a wear. The occurrence of the wear can be explained by the existence of a direct contact with a third body, such as the wear derbies [16]. Wear due to wear derbies are much higher in the space between the brake pads and disc because they cannot "escape" from the contact zone and comes to grinding. These particles become smaller and smaller until they succeed to "escape" from the contact zone or become a part of the secondary plateaus.

The study of contact surfaces i.e. the plateaus in contact showed that the extent of these irregularities depends on the brake pressure. At low brake pressures, the average size of plateaus that has been recorded is in the range of 50 to 500 µm, and represents 10-30% of the nominal area of the brake pads [16]. Under the high pressures and temperatures, the plateaus can reach the size up to one millimeter.

3. NUMERICAL ANALISYS

The performed analysis is dynamic analysis that depends on time. Analysis provided us with an answer regarding the behavior of structures depending on the time under load [17]. Analyzed assembly is shown in Figure 7.

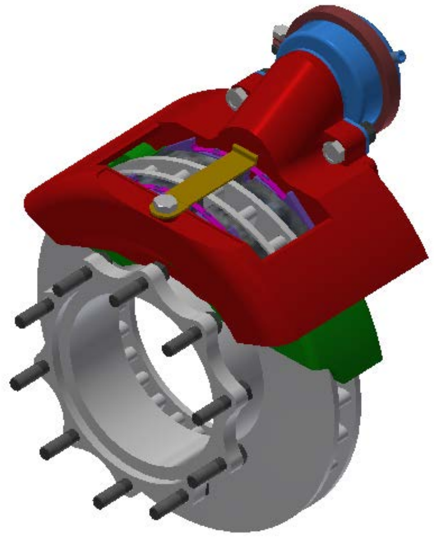

Figure 7: Air disc brakes for heavy duty commercial vehicle

However, as the subject of this paper is tribomechanic analysis of the system - the brake disc and brake pads, only they will be considered. The design of the considered assembly is shown in Figure 8.

3.1. Defining material properties

The mechanical properties of materials used for the analysis of the friction pairs are shown in Table 1. It is necessary first to define the material properties. This was done because the applied software provides properties of general-standard materials. For the specific case, it is necessary to define the properties of the applied material.

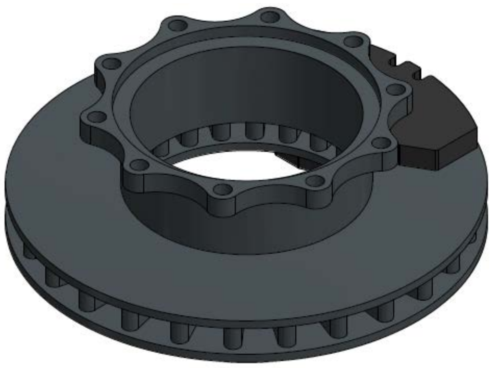

Figure 8: Ventilated disc brake and brake pads

Table 1. Mechanical properties of materials of brake disc and pads [18]

	Disc	Pad
Density [kg/m^3]	2903	2595
Young's modulus [GPa]	113	22
Poison ratio [-]	0.24	0.25
Friction coefficient [-]	0.3 – 0.35	

3.2. Model creating

Various software packages, which have the main task to carry out the structural analysis of the parts and assemblies, are not suitable for the formation of complex models (CAD). They have the possibility of modeling parts, but this design phase is significantly more complicated to perform, in contrast to the software which has the main purpose of creating parts, specifically refers to the applied software package. ANSYS enables import of parts models that have already been created in a software package specifically designed for modeling.

3.3. Boundary conditions

The materials used for this specific case allow the friction coefficient within the range of 0.3 to 0.35 at the pressure of 1 - 2 MPa [18]. Adopted value of the friction coefficient is 0.336, while the value of the pressure is 1 MPa.

After defining the contacts, it is necessary to define the finite element mesh. Disc and pads are shown in Figure 9, in the form of finite elements mash.

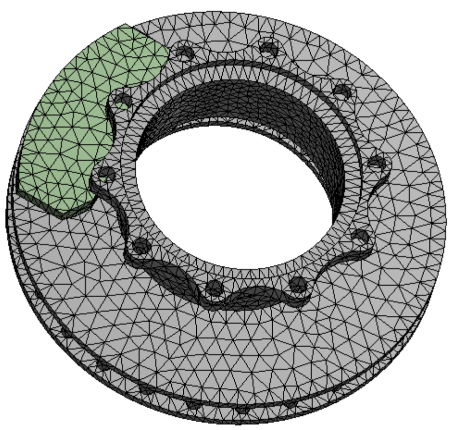

Figure 9: Disc and brake pads represented as the finite element mesh

To achieve a credible analysis that accurately represents what is happening in exploitation of brakes, it is necessary to define the disc's speed at the moment of contact with pads, and the intensity of force pads acting on the disc. Adopted value of pressure pads acting on the disc is 1 MPa. However, it is necessary to specify the load in the form of force. The force the pads acting on the disc is 18340 N. The initial speed of the disc is 10 rad/s, which corresponds to the vehicle speed of 20 km/h.

4. RESSULTS AND DISCUSION

Obtained results in contact of the disc and both brake pads external and internal, are shown in Figures 10-15. Analysis is performed for the disc that is made of MMC materials, while the friction material has the organic origins because it is only possible to achieve a required friction coefficient between these two materials.

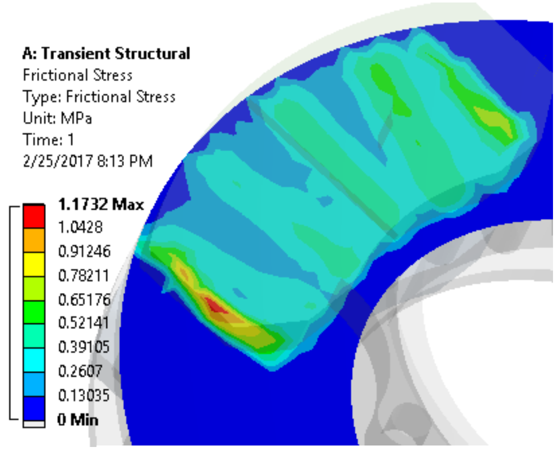

Figure 10: Contact frictional stress at the outside of the disc

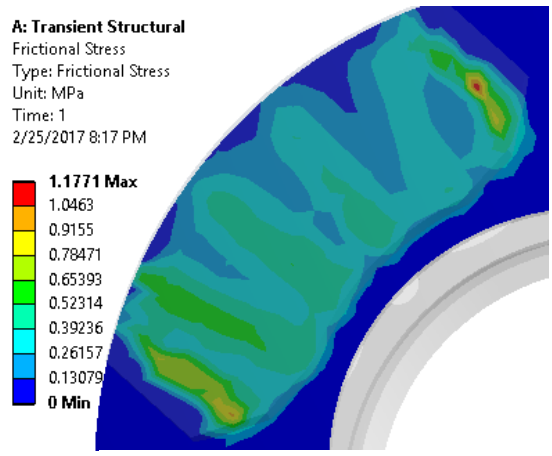

Figure 11: Contact frictional stress at the inside of the disc

Frictional stress that occurs in the contact pair is represented in Figures 10 and 11. The definition of the frictional stress is the stress that occurs between the two elements which slide onto one another, with condition that their contact surface is defined by friction [19]. First, it can be concluded that the higher values are obtained on the inner contact pairs. Observing Figure 10, where the disc rotates in mathematically positive direction, it can be concluded that the highest values of the frictional stress occur in the first part. This is a consequence of the impact load. Furthermore, the same can applies to the inner contact.

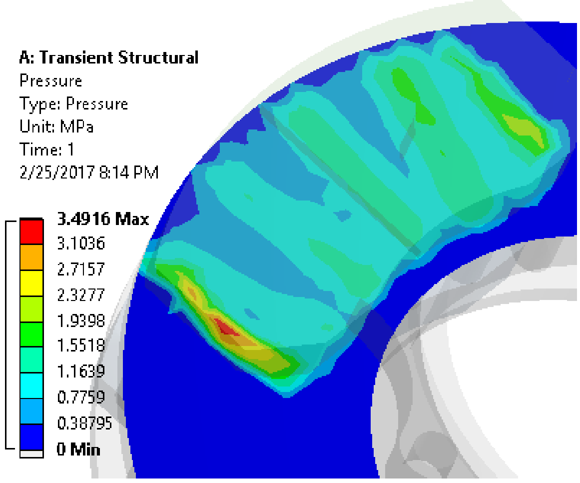

Figure 12: Contact pressure at the outside of the disc

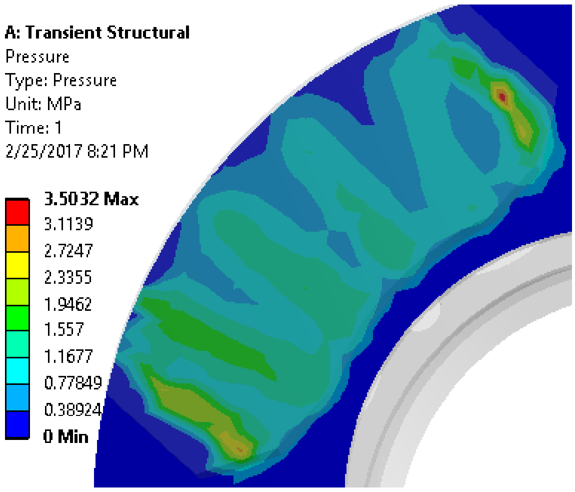

Figure 13: Contact pressure at the inside of the disc

Contact pressure that occurs at the inner and outer side of the disc, is shown in Figures 12 and 13. Furthermore, like in previous case, larger pressures are achieved at the inner side of the disc.

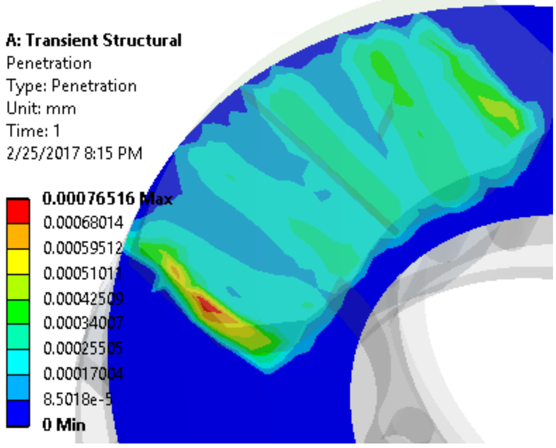

Figure 14: Contact penetration at the outside of the disc

Values of the contact penetration are shown in Figures 14 and 15. However, unlike the frictional stress and pressure, the greater penetration is achieved at the outside of the disc. The highest values of the penetration occur, the same as before, in places where the first contact occurs.

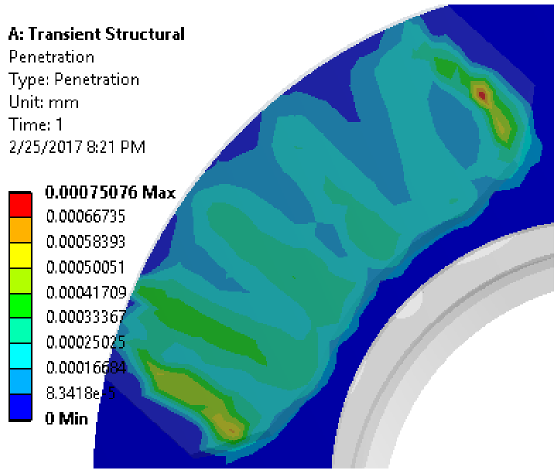

Figure 15: Contact penetration at inside of the disc

Most widely used materials for manufacturing brake discs are cast iron. It is very important to take into account the choice of materials used to produce brake pads. The reason for this lies in the fact that the required friction coefficient can not be achieved between any friction material and disc. The material properties for cast iron, as well as the friction material, which combines wiht the mentioned material is given in Table 2.

Table 2: Material properties of the MMC brake disc and brake pads [20]

	Disc	Pad
Density [kg/m^3]	7250	1400
Young's modulus [GPa]	138	1
Poison ratio [-]	0.28	0.25
Friction coefficient [-]	0.336	

Below is a comparison of the frictional stress, pressure and penetration that is realized whether it is MMC brake discs or discs made of cast iron. Analysis is carried out under the same exploitation conditions.

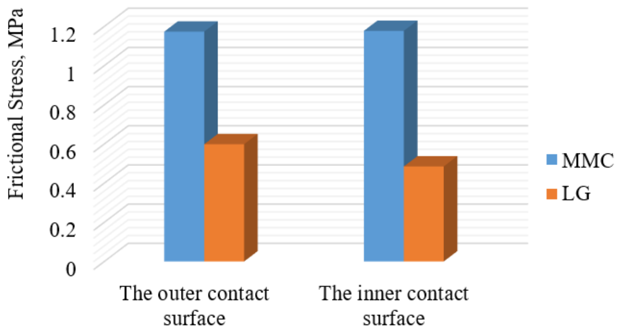

Figure 16: Frictional stress that occurs on the inner and external contact surface depending on the material properties of the friction pair

By observing the Figure 16, it can be noticed that the higher values of frictional stress are realized for discs made of MMC materials. The result of this is that the properties of materials used for the production of discs and brake pads. Comparing the properties of the material used for disc, as well as the materials used for the production of brake pads, it can be seen that they are different. First, the properties of the material used for disc made of MMC are observed, and it has smaller values for all properties compared to the cast iron. While the properties of material use for the brake pads that are combined with the MMC disc, have greater density and Young's modulus of elasticity than the pads that go in combination with cast iron, while the Poisson's ratio is equal.

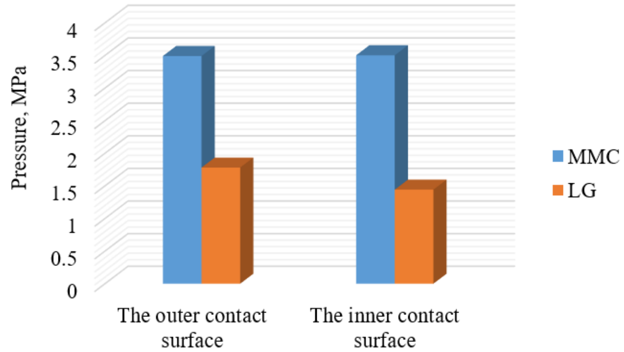

Figure 17: Contact pressure that occurs on the inner and external contact surface depending on the material properties of the friction pair

When it comes to the pressure, it is the same situation as with frictional stress (Figure 17). Higher values occur for discs made of MMC.

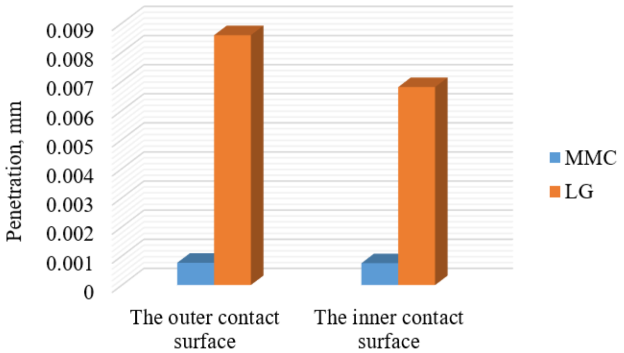

Figure 18: Penetration that occurs on the inner and external contact surface depending on the material properties of the friction pair

At the end, a comparison of penetration values between discs that are made of MMC and cast iron is performed. Unlike the two previous analyses, higher values occur for the discs that are made of cast iron. This means that the higher wear occurs on discs made of cast iron, as shown in Figure 18.

5. CONCLUSION

Obtained results showed that the higher frictional stresses and pressures occur on the inner side of the disc. This directly affects the bending of the friction ring to the outside, so-called „umbrella effect". Higher values of penetration are achieved on the outside of the disc. This is precisely the result of higher values of pressure and stresses that are obtained on the inner side of the friction ring.

Furthermore, one more analysis that shows the comparison between discs made of MMC and of cast iron is performed. Obtained results show that greater pressures and stresses are obtained on discs that are made of MMC, while higher values of penetration occur on disc made of cast iron.

For further research because the emphasis is placed on the alternative materials, it is necessary to modify the materials applied for the analysis. The result would be less value to be obtained for the pressure and stress. Achieved great stresses and pressures can have a major influence on fatigue and can result in catastrophic failure of the brake disc. Furthermore, performed a numerical analysis must be validating by the experiment. Of course, the goal of the research is to start applying MMC discs on the other classes of road vehicles, not just on motorcycles.

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